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Heavy Vehicle Auxiliary Load Electrification for the Essential Power System Program: Benefits, Tradeoffs, and Remaining Challenges

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ABSTRACT

Intelligent management of vehicle auxiliary power can reduce fuel consumed by Class 8 tractor-trailers. Through the U.S. Department of Energy's Essential Power System (EPS) Program, the National Renewable Energy Laboratory is investigating electrification of major mechanically driven auxiliary loads in heavy vehicles. This paper describes the benefits and tradeoffs of a managed EPS and quantifies the potential energy savings of component electrification. Simulations predict that maximum fuel economy increases of 9%–15% (urban drive cycle) and 5%–8% (constant 65 mph) are possible. Future EPS work will require a systems approach with a better understanding of duty cycles and auxiliary needs.

INTRODUCTION

THE ESSENTIAL POWER SYSTEM PROGRAM

The U.S. Department of Energy's (DOE's) Essential Power System (EPS) Program seeks to reduce petroleum consumption by implementing an efficient and practical total-energy management strategy for heavy-duty vehicles. This strategy applies to moving and idling vehicles.

A vehicle's primary mission is moving people and/or goods from one point to another. The focus of an EPS is on the efficient satisfaction of non-propulsion needs. The term "essential" is used in the sense of "only supplying the power that is essential to meet your needs." These needs include primary mission support (e.g., engine cooling and control), passenger comfort (e.g., heating, ventilation, and air conditioning), and safety (e.g., lighting and defrosting). Essential power includes what has traditionally been termed "accessory" or "auxiliary" power.

To reduce U.S. petroleum consumption, significant energy savings must be made using commercially viable solutions. The EPS energy management strategy focuses on essential power management and load reduction. Vehicle integrated energy recovery, energy storage, component electrification, and alternative powering strategies are thought to be key to an efficient EPS. Bringing these concepts into work with industry will help enable practical solutions.

SCOPE OF ANALYSIS

Initially, the EPS Program has targeted Class 7 and 8 long-haul tractor-trailers. EPS technology may also be applied to other platforms, including medium-duty trucks and non-road vehicles (e.g., mining vehicles). This paper focuses on two aspects: describing the energy savings opportunities (tradeoffs) of an EPS and quantifying the potential benefit of removing belt-driven mechanical loads. Remaining challenges are also discussed. The fuel economy impact of replacing mechanical loads with electrical loads is not addressed. Although the energy required to satisfy auxiliary needs is not accounted for, there is merit to looking at the potential fuel savings before "add back" of the electrical power. The EPS Program includes additional elements such as truck idling reduction and base auxiliary load reduction. However, these are not addressed in this paper (see [1] for more information on truck idling reduction).

Justification of the Class 8 Tractor-Trailer Platform

There are approximately 1.5 million Class 7–8 tractor-trailers in the United States [2], and Class 8 long-haul tractor-trailers use more fuel than any other Class 3–8 heavy vehicle [3]. In addition, this platform is relatively uniform as compared to other truck platforms. The platform has significant petroleum savings potential owing to the long travel distances and extended idling of these vehicles. Other vehicle types may yield a greater energy return from EPS optimization on a per-vehicle basis. However, the long-haul tractor-trailer offers the greatest potential to impact national fuel consumption.

Analysis of Auxiliary Components

The auxiliary loads on a moving tractor-trailer (non-refrigerated) that use the most energy are the engine fan, the engine oil pump, the engine coolant pump, the power steering pump, the alternator, the air compressor, and the air conditioning compressor. These devices are examined in a long-haul tractor-trailer scenario. This analysis is detailed in the section titled “Modeling EPS Benefits with ADVISOR.” To understand the system and operational variability involved, two tractor-trailer drive cycles are examined and applicable auxiliary load duty cycles are applied. The accessory power used under these driving scenarios is examined.

Fuel savings resulting from the removal of conventional belt-driven components from the engine are examined. Several auxiliary power units (APUs) are considered to power the electrical system that replaces the mechanical belt-driven devices. The “break-even point” for each APU is identified. The “break-even point” identifies the APU average power that results in a fuel economy equivalent to the baseline unmodified vehicle. Alternative means of satisfying essential power demands are also mentioned.

AUXILIARY DUTY CYCLES

To estimate the savings potential from an EPS, a representative baseline vehicle must first be specified. Fuel energy savings can be predicted by referencing changes from the baseline. Unfortunately, few data exist for in-use essential (auxiliary) power on a tractor-trailer. Where data are available, information on the requirement to be satisfied is often unknown. For example, the power consumption of a mechanical coolant pump versus engine shaft-speed might be available. This information would allow the fuel savings due to the removal of the coolant pump to be quantified. However, the cooling need represented by the mechanical device must still be met. The engine cooling load and efficiency of the replacement device must be known to complete the analysis. Obtaining these data for diverse components and systems can be challenging.

Literature was reviewed to determine representative component duty cycles [4–8]. Two component duty cycles were assembled: the long-haul duty cycle and the local-haul duty cycle. These duty cycles, representing use patterns for accessory devices, differ in the time that a component is on, idling, or disconnected (i.e., not drawing any power). For example, in a local-haul situation, the tractor-trailer is assumed to be in an urban environment. The power requirement for power-steering is usually higher for urban driving than for highway (long-haul) driving. Thus, the power steering pump will demand more power in the local-haul situation.

Each auxiliary device has its own on/off duty cycle (e.g., the air conditioning system may be on 50% of the time). Unrealistic conditions could result from the compounding of on/off component signals for auxiliary devices (e.g., everything “on” or “off” at once). Thus, an attempt was made to evenly distribute the component duty cycles versus time. For example, the available data may indicate that the air conditioning system is loaded 50% of the time, and the power steering may be active 10% of the time. However, a simulation may be unrealistic if the 10% of the time that the power steering is active is always when the air conditioning system is loaded. Instead, signals are spaced out so that all combinations of “on” and “off” can occur among devices.

An attempt was made to decrease unrealistic matching between component duty cycle and vehicle drive cycles as well. For example, if all components are always on during maximum vehicle acceleration, this may bias the results. Our solution was to simulate a given drive cycle several times back-to-back. The difference in periods between the drive cycle and auxiliary duty cycle provides for a reasonable amount of averaging. This is shown in Figure 1. Further investigation was deemed unnecessary, because predicted fuel economy was relatively insensitive to cycle matching over the simulations conducted.

ESSENTIAL POWER AND DUTY CYCLES

Table 1 shows estimates of the accessory power used by conventional heavy vehicle components. The data were used to establish a realistic conventional baseline. Table 2 shows the duty cycles of these components. Figures 2–7 show component power consumption referenced to engine shaft speed for the conventional vehicle baseline [4–7].

Figures 5 and 7 show oil pump and coolant pump loading. The engine map data were collected with the engine coolant pump and oil pump integrated with the engines. Thus, these components can be considered part of the engine fuel efficiency map (the fuel efficiency map gives fuel consumption by engine shaft torque and speed). Oil pump or coolant pump removal is simulated with a negative power added to the engine shaft demand.

The alternator efficiency map used in this paper is adapted from Schmidt et al. [8]. A generation requirement of approximately 0.6 kW of electricity was assumed on average, based on calculations from SAE J1343 [4].

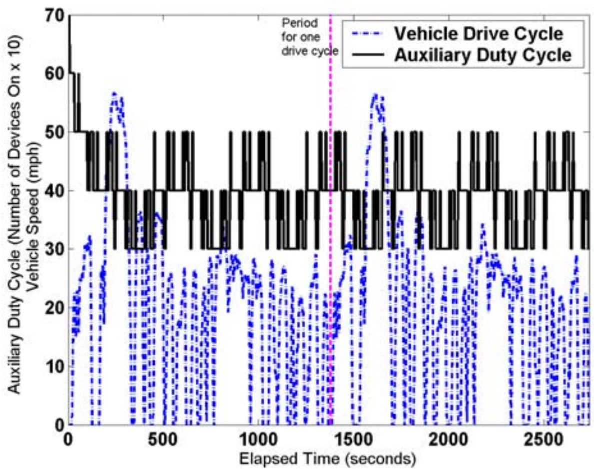

Figure 1. Combination of Auxiliary Duty Cycle and Vehicle Drive Cycle to Reduce Unrealistic Compounding of the Two Signals. Note the difference in number of auxiliary loads engaged between the 55 mph peak in the first and second drive cycles.

Table 1. Conventional Component Power Requirements [4–6]

Component name	**Local haul** **Power required (kW)**		**Line haul** **Power required (kW)**	
	Max. power	**Avg. power**	**Max. power**	**Avg. power**
A/C compressor	4.5	2.2	4.5	2.2
Power steering	4–11	2.4–6.6	4–11	0.4–1.1
Air brake compressor	Pumping 6.0 No load 2.4	3.5	Pumping 6.0 No load 2.4	2.3
Engine fan	15–30	1.5–3.0	15–30	0.8–1.5
Alternator	Variable (1 kW max. /0.7 kW avg. [4])			
Oil pump	4.5	NA	4.5	NA
Coolant pump	2	NA	2	NA

Table 2. Component Duty Cycles [4]

Component name	**Line-haul duty cycle (% of time on)**	**Local-haul duty cycle (% of time on)**
A/C compressor	50%	50%
Power steering	10%	60%
Air brake compressor	5%	30%
Engine fan	5%	10%
Alternator	100%	
Oil pump	100%	100%
Coolant pump	100%	100%

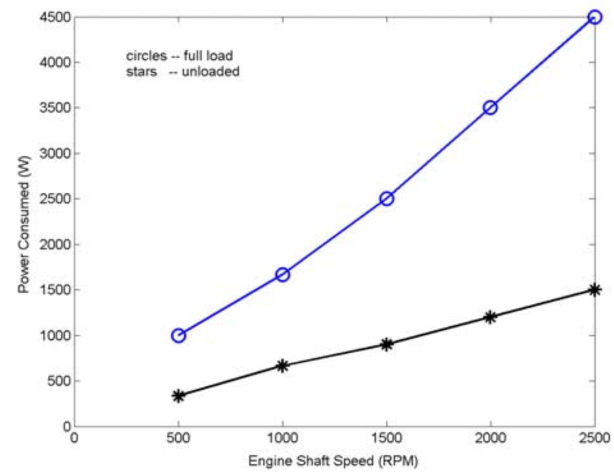

Figure 2. Air Brake Compressor Loading vs. Engine Shaft Speed

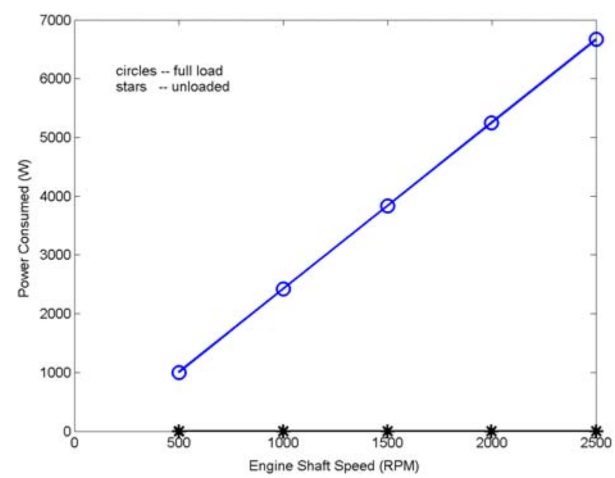

Figure 3. Air Conditioning Compressor Loading vs. Engine Shaft Speed

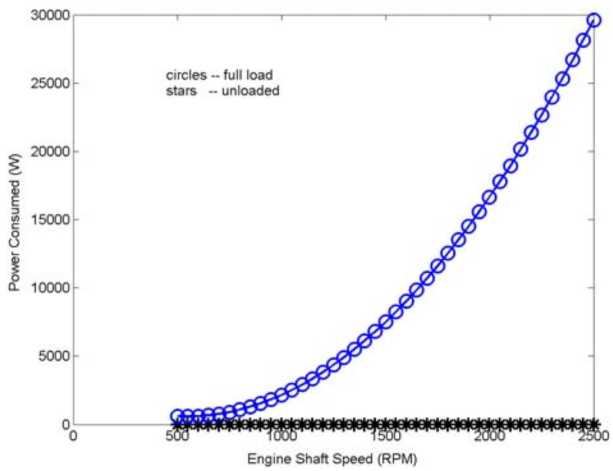

Figure 4. Engine Fan Loading vs. Engine Shaft Speed

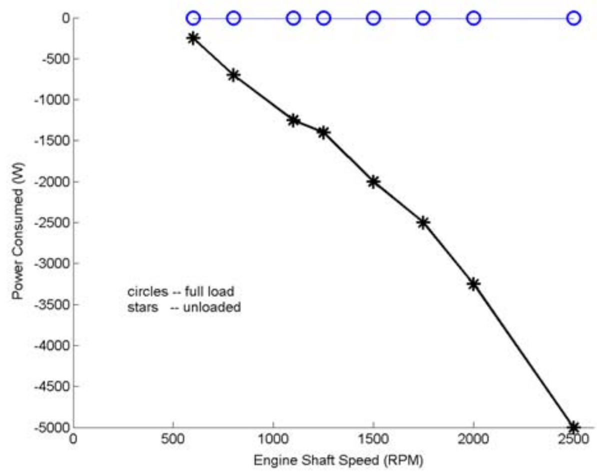

Figure 5. Oil Pump Loading vs. Engine Shaft Speed

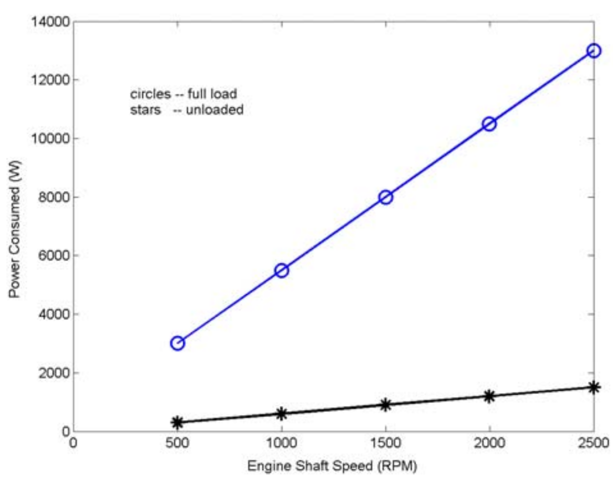

Figure 6. Power Steering Loading vs. Engine Shaft Speed

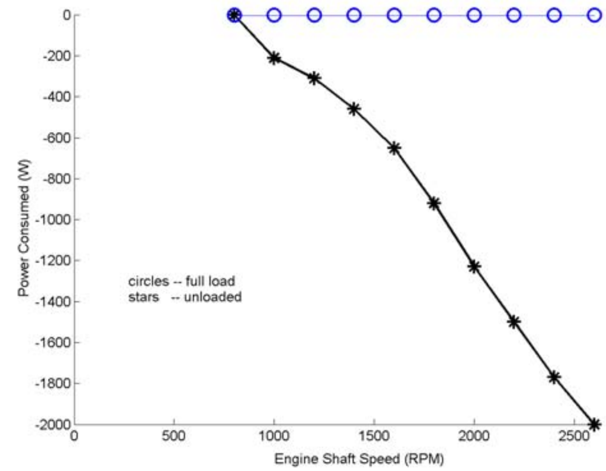

Figure 7. Coolant Pump Loading vs. Engine Shaft Speed

Figures 2–7 illustrate how energy can be wasted with mechanical belt driven accessories. Power consumed by auxiliary devices varies with belt speed but not with load requirement. For this reason, mechanical devices tend to be oversized for typical duty cycles. Furthermore, some devices draw power even when not performing useful work as indicated by positive values for unloaded power consumption.

ESSENTIAL POWER SYSTEM ENERGY TRADEOFF

Energy saved by management of essential power comes from optimizing the following energy tradeoff equation:

Energy Savings =

- (energy lost due to decrease in power plant average efficiency)

+ (energy saved due to elimination of unloaded mechanical accessory power consumption)

+ (energy saved due to elimination of loaded mechanical accessory power consumption)

- (energy lost due to loaded electrical accessory consumption)

- (energy lost due to energy required to accelerate and roll extra mass)

+ (energy saved due to elimination of truck-stop idling)

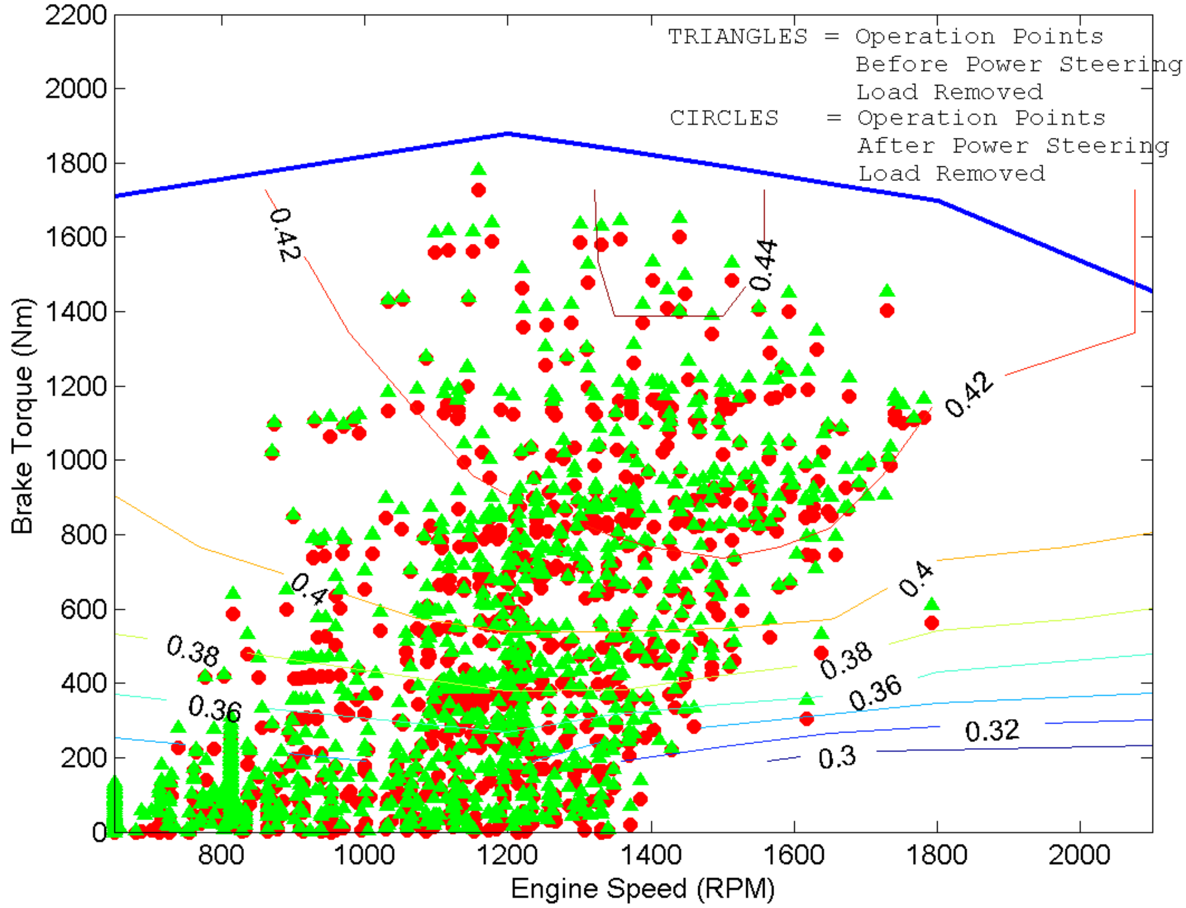

Figure 8. Engine Operation Points Before and After Mechanical Power Steering Load Removed

ENGINE EFFICIENCY CHANGES

In general, a loaded internal combustion engine decreases in efficiency when unloaded (all else being equal). This phenomenon is addressed with the first term of the energy tradeoff equation. This is observed (in simulation) when auxiliary power demand is removed from the engine. Figure 8 depicts an engine map consisting of efficiency contours by shaft brake torque and engine shaft speed. Triangles represent the baseline engine running a power steering load over a normal drive cycle. Circles show the operation of that same engine over the same drive cycle, but with the power steering load removed from the engine.

From simulation, the conventional mechanically driven power steering uses 1.77 kWh of energy from the engine over the drive cycle. The initial cycle-averaged engine efficiency is 33.7%. Removing the power steering from the engine should save the following amount of fuel energy:

$$\text{Energy savings} = \frac{1.77}{0.3368} = 5.26\,\text{kWh}$$

However, the actual fuel energy saved is only 1.93 kWh. As shown in Figure 8, the operating points “slide” down the efficiency contour. The net effect is to change the cycle-averaged engine efficiency from 33.7% to 31.7%. This change in cycle-averaged efficiency causes an apparent loss of 3.33 kWh of fuel energy. This is due to the vehicle roadload having to be satisfied with a lower average engine efficiency. If the cycle-averaged engine efficiency remained constant for both cases, the full 5.26 kWh of energy could be saved.

In terms of actual fuel economy, the numbers translate as follows. The baseline fuel economy is 4.48 mpg (57.6 kWh of fuel energy). Removing the conventional power steering load increases fuel economy to 4.64 mpg (55.67 kWh of fuel energy). If the efficiency were to remain constant, fuel economy would be 4.93 mpg (52.34 kWh of fuel energy). For low mile-per-gallon numbers, a 0.45-mpg improvement is significant (equivalent to 20 gallons of fuel saved per 1000 miles traveled).

Changes in efficiency due to removal of accessory loads are more pronounced in urban transient cycles. However, the same phenomenon can be seen during highway driving as well.

Engine downsizing or re-tuning could enable the unloading of an engine without sacrificing efficiency. Linear engine resizing is used in this study. Results are presented in the section titled "Modeling EPS Benefits with ADVISOR." With linear engine resizing, the efficiency map contours are shifted down linearly in torque. The extent of resizing has been constrained by maintaining constant performance characteristics (acceleration and gradability). Thus, the resized engine without accessory power loads has equivalent performance to the base engine with all accessory loads enabled. In the linear resizing method, performance constraints prevent full recovery of the efficiency lost due to unloading.

REMOVAL OF CONVENTIONAL LOADS

Energy is saved when traditional belt-driven mechanical loads are removed from the engine. The second and third terms of the energy tradeoff equation address the removal of belt-driven mechanical devices.

The needs that the belt-driven mechanical devices satisfy will be addressed with electrical components. Component electrification is discussed in the section titled "Powering Electrical Devices." This section examines the savings potential and reasons for removing traditional belt-driven mechanical devices. For additional discussion, see Hnatczuk et al. [5].

The energy savings from removal of belt-driven mechanical devices are split into two terms for illustrative purposes. The first term represents removal of power required from the engine for devices that are idling. The second term addresses devices that are loaded and are active. Energy saved by cutting power sent to idling devices is a pure savings. Idling devices do not perform useful work. They are merely coupled mechanically with the engine and create a parasitic drag. In contrast, energy saved by removing loaded mechanical devices must be metered back (electrically) to satisfy auxiliary needs. However, the mechanical and electrical power requirements are not necessarily the same.

The performance of traditional belt-driven mechanical devices is engine shaft speed dependent. These devices are not controlled but are instead subject to the vehicle driving cycle. As such, traditional belt-driven mechanical devices tend to be oversized to meet worst-case design points. Moving to a controllable electrical system allows the applied power to more efficiently address the load-following requirement.

POWERING ELECTRICAL DEVICES

A source of on-board electrical energy is required for component electrification. Possible sources of electricity on a truck are APUs, integrated generation, shore power, and/or energy storage. APUs include devices such as gas microturbines, small internal combustion engines (i.e., gensets), and fuel cells. Integrated generation includes concepts such as mild hybridization, electro-turbo compounding, and thermoelectrics. Mild hybridization would allow direct generation of electricity from the engine through devices such as an integrated starter generator. Electro-turbo compounding is a technique to generate electricity from engine exhaust gasses. Thermoelectrics are devices that can generate electricity from engine waste heat. Shore power is the use of land-based electricity when the vehicle is stopped. Lastly, energy storage systems (e.g., batteries and ultracapacitors) could provide electrical power but would require a means of recharge. Figure 9 gives an overview of these possible electrical power paths.

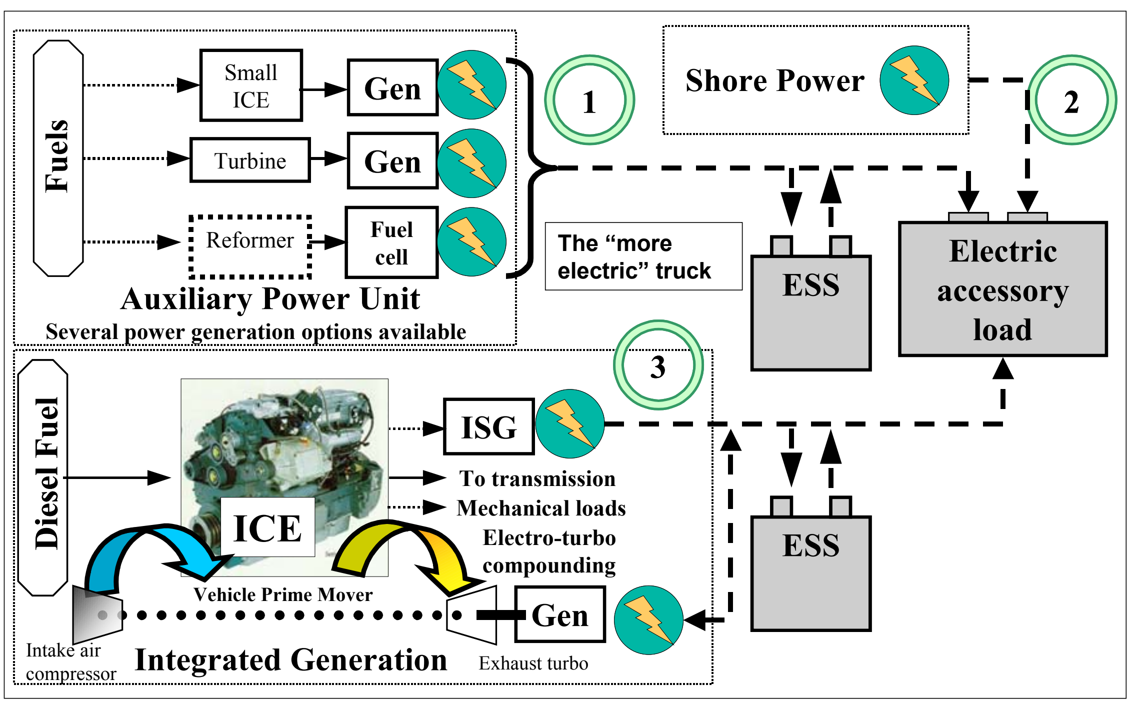

Figure 9. Three Power Paths for Electrical Power Generation: Auxiliary Power Unit, Shore Power, and Integrated Generation. Dashed lines are electrical energy paths. Dotted lines are mechanical or chemical energy transfers. ESS—energy storage system; Gen—generator; ICE—internal combustion engine; ISG—integrated starter generator.

Three APUs are examined in this paper: a diesel-electric generator set, a proton exchange membrane fuel cell, and a solid oxide fuel cell plus advanced thermoelectrics. For the APU, the break-even point is determined. The "break-even point" is defined as the point at which all the energy saved by removing the mechanical loads is used to power electrically driven systems. The concept of a "break-even point" is illustrated in Figure 10. See the section titled "Modeling EPS Benefits with ADVISOR" for further details.

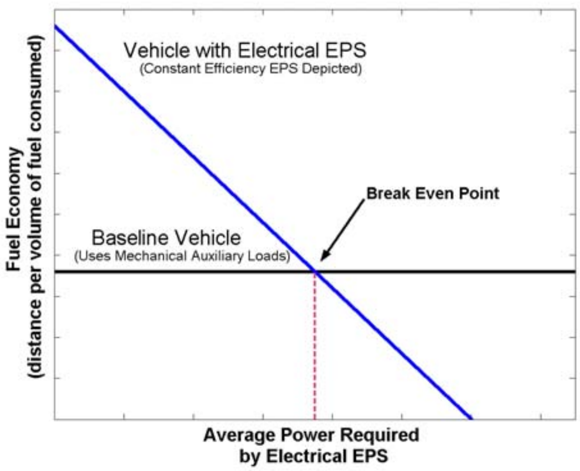

Figure 10. Depiction of the "Break-Even Point"

CHANGES IN MASS

Vehicle net mass may change with the adding and subtracting of components and due to engine downsizing. The change in mass affects energy required for acceleration and energy dissipated to overcome rolling resistance. This study accounts for the effect of mass on vehicle fuel economy. On a practical level, increases in mass may only displace cargo, and net vehicle mass may remain constant. Either way, mass increases (resulting in increased vehicle weight or displaced cargo) are unfavorable.

MODELING EPS BENEFITS WITH ADVISOR

Modeling was conducted using the ADVISOR software from DOE's National Renewable Energy Laboratory (NREL). ADVISOR is a free, open source, downloadable software program that runs in MATLAB/Simulink [9–11]. In this study, a heavy-vehicle version of ADVISOR is used to quantify changes in fuel economy due to the removal of mechanical belt-driven loads from a baseline Class 8 tractor-trailer.

The baseline truck is modeled loosely after the Ralph's Grocery Fleet Class 8 tractor-trailer delivery truck [12]. The average measured fuel economy from the Ralph's Grocery fleet is 4.97 mpg with a standard deviation of 0.3 mpg for the CSHVR (City Suburban Heavy Vehicle Route) cycle [13]. The baseline model used in this paper has a fuel economy of 4.48 mpg. An exact match is not expected owing to lack of data to fully model the Ralph's Grocery truck. Also, the model is probably using a higher auxiliary power load than was experienced during the chassis dynamometer tests in the Ralph's Grocery Fleet study [12]. Table 3 shows the characteristics for the ADVISOR model.

Table 3. Characteristics of Baseline ADVISOR Truck Model

Characteristic	**Value**
Vehicle mass	19,090 kg
Baseline fuel economy	4.48 mpg (simulated CSHVR) 6.22 mpg (simulated 65 mph) 4.86 to 5.0 mpg (vehicle chassis dynamometer over CSHVR)
Transmission	TX_RTLO12610B (Eaton Fuller 10-speed transmission)
Rolling resistance coefficient	0.00938
Coefficient of drag	0.7
Frontal area	8.55 m^2

VEHICLE DRIVE CYCLES

The drive cycles examined in this paper are a constant 65-mph cruise and the CSHVR drive cycle. CSHVR stands for "City Suburban Heavy Vehicle Route" and is a cycle developed by West Virginia University [13]. Each drive cycle has a corresponding auxiliary load duty cycle based on SAE J1343 [4]. The constant 65-mph cycle uses the line-haul duty cycle for various auxiliary components. The CSHVR drive cycle uses the local-haul duty cycle for various auxiliary components.

VEHICLE ENGINE MAPS

Caterpillar provided publicly available engine performance specifications for much of the company's current heavy-duty engine line. These data are used in conjunction with existing ADVISOR engine maps to examine how the analysis might vary by engine type. Table 4 gives a list of engine maps used in this paper. These engine maps are available in ADVISOR 2002 [11].

Table 4. Engine Map Descriptions

Engine map name	Description
FC_CI324	Engine map based on performance information from Caterpillar C-15 and DDC series 60 engine map
FC_CI321	Engine map based on performance information from Caterpillar C-12 and DDC series 60 engine map
FC_CI250	Engine map based on performance information from Caterpillar C-10 and DDC series 60 engine map
FC_CI330	Engine map based on Detroit Diesel Series 60 engine
FC_CI205 scaled by 1.5605	Engine map based on Detroit Diesel Series 50 engine

POTENTIAL FUEL ECONOMY IMPROVEMENT

The potential range of increase in fuel economy over the two drive cycles and the components examined are given in Figure 11, which compares the expected percentage increase in fuel economy due to removal of the given mechanical auxiliary load. The fuel penalty required to “add back” the missing functionality is not accounted for. Weight effects are also neglected.

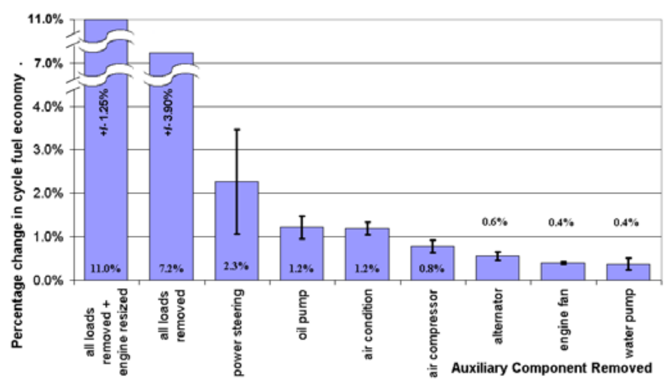

Figure 11. Range of Fuel Economy Improvement Estimates by Component

The range shown in Figure 11 as error bars is calculated by taking the minimum and maximum benefit seen over the combination of engine maps and drive-cycles examined. The power steering, oil pump, air conditioner, and air compressor give the largest single improvements. Note that the benefit of removing all mechanical auxiliary loads yields a much higher impact than any one device individually. This would seem to indicate that a total systems approach will be much more effective than a “piecemeal” solution. We are recommending that the EPS Program follow a systems approach for this reason.

Figures 12 and 13 display percentage improvement in fuel economy when all mechanical loads are removed from the engine. This analysis is conducted over five engine maps, two drive cycles, and four added mass conditions.

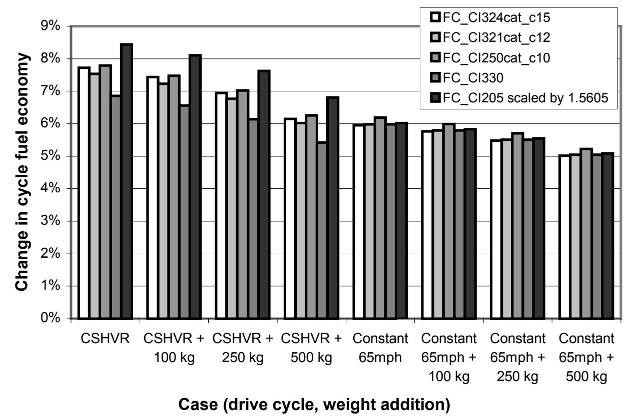

Figure 12. Percent Increase in Fuel Economy by Drive Cycle, Weight Addition, and Engine Type

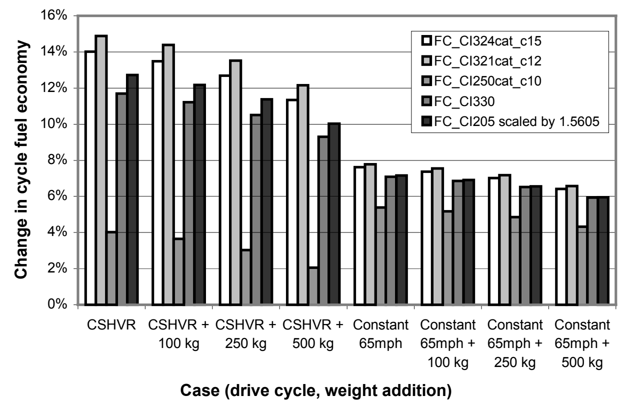

Figure 13. Percent Increase in Fuel Economy by Drive Cycle, Weight Addition, and Engine Type (Engine Resized)

Figure 13 shows the possible improvements if the engine is resized. The resized engine is scaled linearly such that the resized engine has the same performance (i.e., acceleration and gradability) as the original engine with full accessory loading.

The decrease in performance seen with the FC_CI250 engine map upon resize is not a mistake. This engine was too small for the original application and, upon resize, was made larger to meet the baseline performance constraints.

Figures 14 and 15 show the maximum predicted fuel savings per 1,000 miles traveled over the CSHVR and constant 65-mph drive cycles. They depict the fuel savings possible by removing conventional mechanical auxiliary devices from an engine. The essential power required to meet the auxiliary needs electrically has not yet been calculated.

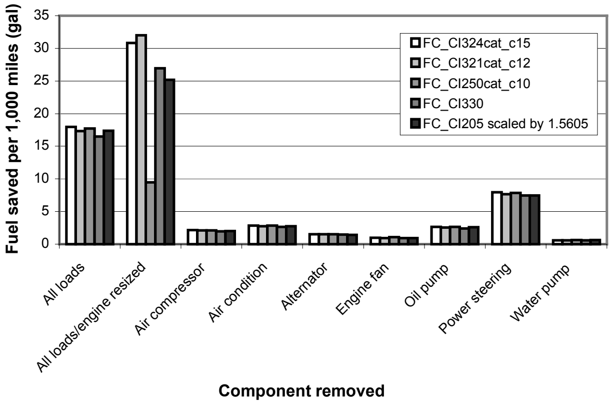

Figure 14. Gallons of Fuel Saved per 1,000 Miles on CSHVR Drive Cycle

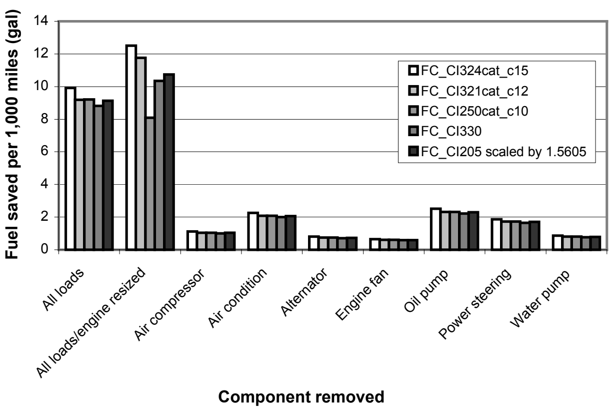

Figure 15. Gallons of Fuel Saved per 1,000 Miles on Constant 65-mph Drive Cycle

Novel techniques such as electro-turbo compounding, which uses exhaust gas to generate electricity, could easily supply load demands during 65-mph driving [6]. However, this would presumably change the engine backpressure and decrease fuel economy. Other techniques such as thermoelectric power generation may be able to capture wasted thermal energy without negatively affecting fuel economy [14].

Another possibility for electrical generation is an APU. An APU would be the power plant for a dedicated electrical EPS. The essential power required to meet auxiliary needs will be a focus of the next phase of our EPS work at NREL. To get a feel for the maximum electrical load that could be applied, several “break-even analyses” have been conducted. The break-even analyses appear in Figures 16–21. Note that Figures 19–21 use engine downsizing, which allows for higher fuel savings. Note that many of the APU configurations break-even at greater than 6 kW (electric) average power output for 65 mph.

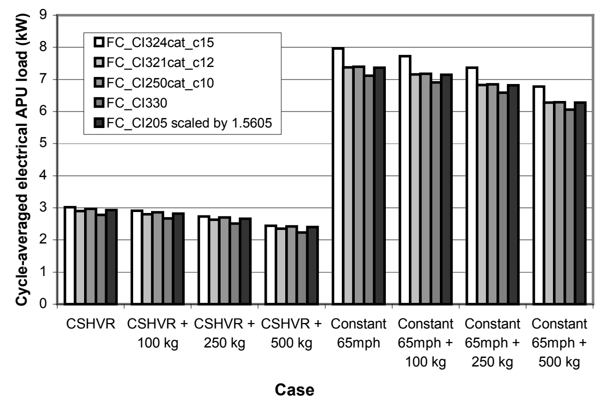

Figure 16. Break-Even Values of 32.3% Efficient APU (e.g., diesel-electric generator set)

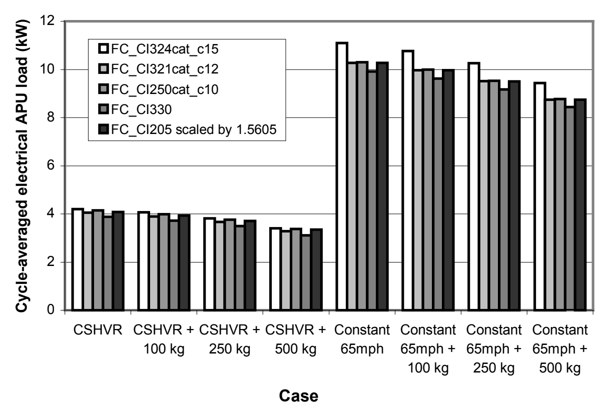

Figure 17. Break-Even Values of 45% Efficient APU (e.g., proton exchange membrane fuel cell)

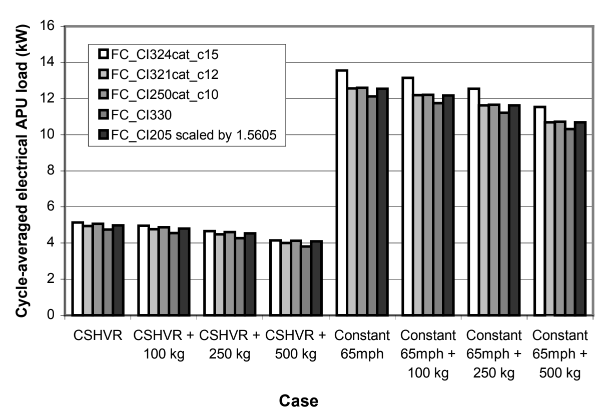

Figure 18. Break-Even Values of 55% Efficient APU (e.g., solid oxide fuel cell plus thermoelectrics). To achieve 55% efficiency, advanced thermoelectric devices will be required—this is certainly an upper bound.

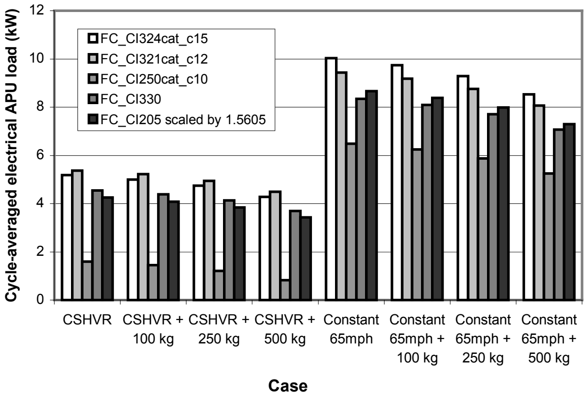

Figure 19. Break-Even Values of 32.3% Efficient APU (e.g., diesel-electric generator set) and Engine Resized

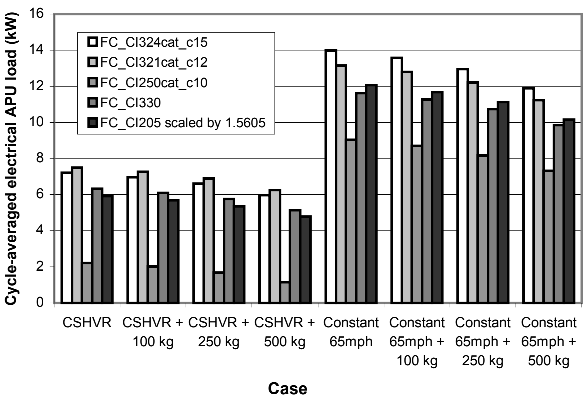

Figure 20. Break-Even Values of 45% Efficient APU (e.g., proton exchange membrane fuel cell) and Engine Resized

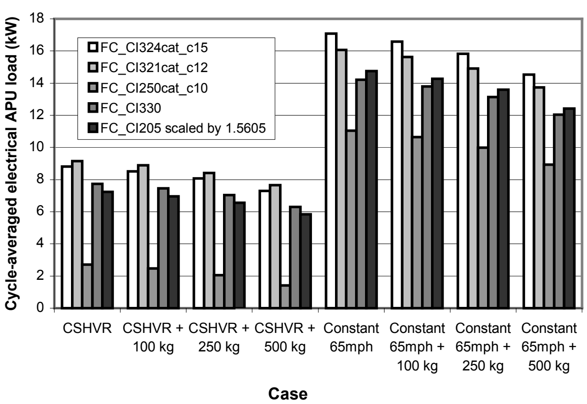

Figure 21. Break-Even Values of 55% Efficient APU (e.g., solid oxide fuel cell plus thermoelectrics) and Engine Resized. To achieve 55% efficiency, advanced thermoelectric devices will be required—this is certainly an upper bound.

REMAINING CHALLENGES

As with any new technology, a commercially viable EPS will have to pass traditional hurdles such as cost, durability, and reliability. These are not trivial challenges. The need for a systems approach to address the EPS concept and program objectives cannot be overemphasized. As part of this, a better understanding of the actual duty cycle and loads of Class 8 tractor-trailers is needed. This includes accessory energy use patterns both while the vehicle is moving and while at idle. In addition, a better understanding of the requirements that accessory loads satisfy is required. This will allow opportunities to reduce auxiliary loads and optimize auxiliary devices to their loads.

CONCLUSION

Significant fuel savings can be realized through intelligent management of essential power. The Class 8 tractor-trailer constitutes a good target platform for introduction of an EPS. The final energy savings that can be derived from an EPS involves many tradeoffs. Vehicle fuel consumption will be affected by changes to engine loading and sizing, auxiliary electrification, base need reduction, mass effects, and idling reduction.

NREL's vehicle simulation code, ADVISOR, has been modified for heavy vehicle simulation and used to quantify the potential benefit of an EPS. Simulation indicates that for a tractor-trailer driving at a constant 65 mph, the maximum fuel savings are 5%–8% when all mechanical loads are removed from the engine and the engine is resized. For the CSHVR cycle, estimated savings are from 9% up to 15% if the engine is resized. These estimates do not account for the energy required to satisfy the auxiliary needs previously satisfied by the mechanical devices. However, technologies such as thermoelectrics and electro-turbo compounding, which generate electricity from waste energy, may be able to provide power for some or all of the auxiliary devices. Further investigation is necessary.

A break-even analysis was presented to identify the APU average power that results in a fuel economy equivalent to the unmodified baseline vehicle. For electrical essential power loads, a break-even steady state APU output power of 6–17 kW over a constant 65-mph driving cycle is possible depending upon added system weight, engine type, engine resizing, and assumptions about the APU. For the CSHVR cycle, break-even values are 2–9 kW.

The technical challenges required to implement an EPS are not trivial. A full systems approach coupled with a better understanding of duty cycles and EPS requirements will be required.

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